Movement Form of the Overarm Throw for Children at 6, 10 and 14 Years of Age

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Abstract

This study investigated overarm throwing technique at different developmental ages in children from the perspective of three distinct, though potentially complementary, approaches to motor skill acquisition. Children at 6, 10, and 14 years of age (N = 18), completed dominant overarm throws during which whole-body kinematic data were collected. Firstly, application of Newell's (1985) stages of learning identified three distinct age-related coupling modes between forward motion of the centre-of-mass (CoM) and the wrist, which demonstrated a greater range of couplings for older children. Secondly, in line with Bernstein's (1967) hypothesis of freezing before freeing degrees of freedom, a significantly smaller range of motion (ROM) at the ankle and knee joints, but greater ROM at the hip and upper limb joints was found for the 6 year old group compared to the 10 and 14 year old groups. Thirdly, based on the components model (Roberton & Halverson, 1984), the overarm throws demonstrated by 6 year olds were characterised as primitive to intermediate, where 10 and 14 year old's throws were characterised by the penultimate action level for each component. Characteristics of CoM-wrist coupling more clearly identify children's age-related technique and highlight the importance of posture-ball release dynamics. The posture-ball dynamics were supported by changes in ROM and the components model, revealing the complementary nature of the 3 approaches to the analysis of age-related differences in overarm throwing action.

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The overarm throw is a fundamental movement pattern that requires coordination and control of the limb and torso segments of the whole-body (Robertson & Halverson, 1984; Van den Tillaar, & Ettema, 2007), particularly when the task demands (distance, time, accuracy etc.) are toward the upper end of the performance capacity of the individual throwing. Children typically learn to throw in early and middle childhood in both home and school contexts. Throwing requires the formation of a stable but flexible movement pattern (technique) to eventually release a range of task outcomes with maximal certainty and efficiency (Keller, Lamenoise, Testta, Golomer & Rosey, 2011; Palmer, Newell, Gordon, Smith & Williams, 2018; Roberton & Halverson, 1984; Stodden, Langendorfer, Fleisig & Andrews, 2006a,b; Yan, Payne & Thomas, 2000).

The majority of studies on throwing have investigated children learning to throw an object (usually a small ball that can be held in one hand) with their dominant arm towards a target goal for accuracy, speed or both (Halverson, Roberton & Langendorfer, 1982; Roberton & Halverson, 1984; Roberton, Halverson, Langendorfer & Williams, 1979; Roberton & Konczak, 2001). Early studies measured properties of the throwing pattern via a rating scale approach (Halverson et al., 1982; Roberton & Halverson, 1984; Roberton et al., 1979). In more recent research, greater use of motion capture devices that provide the capacity for recording the kinematic details of the thrower's movement have been used (Stodden et al., 2006a,b; Yan et al., 2000). However, there are few studies that have taken advantage of the full capacity of motion capture and analysed the kinematics of the arm motion in throwing along with the kinematics of the whole-body motion so as to examine the important role of postural support in learning to throw or performance on any single throw (Palmer et al., 2018).

Capturing whole-body actions is particularly important since research supports the theoretical proposition that motor control is organized with overall system dynamics at the centre (Kelso, 1995; Newell, 1985). From this view the overarm throwing movement might be underpinned by the coordination of the arm motion to the postural motion (single step, trunk rotation). In order to study this proposition further, integrated approaches that encompass posture and ball release dynamics need to be applied.

Three different though potentially complementary approaches are used here to examine technique of overarm throwing at different ages: Newell's (1985) stages of learning coordination, control and skill; Roberton and Halverson's (1984) components model of overarm throwing; and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom. It is anticipated that the combination of approaches can provide a more comprehensive understanding of the change in technique with age and better inform understanding of the processes and mechanisms by which changes to the system occur with age, and so inform skill development.

In more detail, Newell's (1985) stages of learning provides a dynamical systems approach to motor skill acquisition which offers a functional distinction between the constructs of coordination, control and skill. Based on the interaction of the organism, environment and task constraints leading to a self-organised movement outcome, Newell (1985) did not prescribe the specific variables to quantify the stages of learning. Rather, it was hypothesised that these variables would be task specific. For example, no specific characteristics of joint or body actions were proposed that related to skill level, 'coordination' or 'control'. One aspect that was stipulated however, was that as skill level increased dysfunctional variability would decrease, allowing the performers to cope with perturbations presented by the task and environment. In answer to the problem of what variables to study to capture 'technique' and technique change, recent work by Newell and colleagues has emphasised macroscopic variables that capture the global topological space-time properties of the system's coordination patterns. For example, paralleling the phase relation between fingers used in the HKB model (Haken, Kelso, & Bunz, 1985; Kelso, 1995), relationships between centre of mass (CoM) and centre of pressure have been investigated (Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017; Ko, Challis, & Newell, 2014). Translating these ideas to study changes in non-dominant overarm throw technique in adults, Palmer et al. (2018) investigated motion of the CoM and wrist as adults practiced a non-dominant overarm throw. Practice induced changes in the CoM-wrist coupling, where this coupling became more complex and less variable with practice. It is of interest to determine if CoM-wrist coupling is also able to identify common technique in overarm throwing action as a function of developmental age. Thus, the current study applies the methods outlined by Palmer et al., (2018) but for a more representative group of children. It was hypothesised that the relationship between the motion of the CoM (postural variable) and the wrist (end effector) could capture generalizable age-related changes in the macroscopic organisation of the system in this throwing task and the link between postural support and instrumental limb action.

Secondly, Roberton and Halverson (1984) developed the components model of overarm throwing following a 7 year longitudinal study of a single cohort of 39 children from the ages of 6 to 13 years. As seen in Table 1, the components model is based on a qualitative assessment of motions of body segments or groups of segments (feet, trunk, humerus and forearm) during the throwing action, with a rating scale that categorises an individual's throwing action with each on a continuum of 3 or 4 stages (Table 1). As the only specific overarm throwing model of technique changes, the components model has been applied to examine technique changes in children (Keller et al., 2011; Langendorfer & Roberton, 2002; Roberton & Konczak, 2001; Stodden, et al., 2006a,b).

Thirdly, Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom captures technique changes at the joint-space level.

Investigating whether more joint actions are involved from proximal to distal with practice, changes in joint angle range of motion (ROM) have been explored during learning novel tasks (Chow, Davids, Button & Rein, 2008; Newell, Kugler, Van Emmeik & McDonald, 1989; Vereijken, Whititing & Beek, 1992). It is also noted that dynamical degrees of freedom, such as coordination variables, have been defined and studied (Ko, Challis, & Newell, 2003: Verhoeven & Newell, 2016). The direction of freezing and freeing seems to be task specific and dependent on the level of the system being analysed during learning (Hong & Newell, 2006; Newell & Vaillancourt, 2001). In order to study Bernstein's (1967) hypothesis, biomechanical analysis of ROM is used here to provide information about technique changes at individual joint level.

In a parallel study, Palmer et al. (2018) investigated the evolution of change in technique of the non-dominant overarm throw as a function of a 3 week period of practice in adult learners using the above three distinct approaches. Practice induced changes in the CoM-wrist coupling were supported by individual strategies at the joint-space level revealing the complementary nature of the three approaches. It is of interest to determine if CoM-wrist coupling is also able to identify common technique changes in overarm throwing action as a function of developmental age and whether individual strategies exist at the joint-space level. The current study applies the methods outlined by Palmer et al. (2018) but for a more representative group of children. Understanding the characteristics associated with technique change during skill acquisition of a motor task in childhood can provide valuable insight in to the task demands of the whole body.

The study reported here examines overarm throwing action of a cross-section of children's ages that relate to distinct developmental age periods (Meister, Day, Horodyski, Kaminski, Wasik & Tillman 2005; Mickle, Munro & Steele, 2011; Roberton & Halverson, 1984; Stodden et al., 2006a,b). The purpose was to establish: (1) if current approaches to motor learning have adequately described dominant overarm throw technique differences at 6, 10 and 14 years of age – particularly in the link of throwing arm to posture, trunk rotation and a step; and (2) if differences in technique across age are consistent with changes that occur during learning non-dominant overarm throw in adulthood as revealed in Palmer et al. (2018). Finding the latter relation would provide evidence that the typical poorer throwing technique of the non-dominant arm is primarily due to environmental effects namely, the lack of practice and relevant throwing experience.

The hypothesis examined was whether individual-specific quantitative differences in joint ROM and qualitative changes in Roberton and Halverson's model are embedded within age-related differences in the relative motion of the CoM-wrist.

Methods

Participants

Ethical approval was granted from the host University's Ethics Committee prior to study initiation. Analysis was performed on 18 children split into three age groups: 6 years (5 females, 1 male; age 6.56 ± 0.30 years, stature 1.22 ± 0.05 m and mass 23.88 ± 5.02 kg), 10 years (4 females, 2 males; age 10.32 ± 0.33 years, stature 1.47 ± 0.10 m, mass 39.29 ± 3.26 kg) and 14 years (4 females, 2 males; age 14.22 ± 0.48 years, stature 1.64 ± 011 m, mass 61.02 ± 6.97 kg).

All participants provided assent alongside parent/guardian written informed consent. Parent/guardians also completed a pre-exercise health questionnaire and the Edinburgh handedness inventory (Oldfield, 1971) on behalf of their child. Inclusion criteria at recruitment were as follows: participants were not competing in a throwing-based activity, had a dominant hand, and were free from musculoskeletal injury.

Procedures

Each participant attended a single data collection session. Kinematic data were collected for 5 overarm throws performed with the dominant arm. Overarm throws were completed from a standing position, with each participant free to choose their preferred stance. Participants were given the aim of hitting 0.4m target located 14 m in front of them by throwing a standard issue tennis ball (Slazenger) ball as hard as possible. The target height was adjusted to each participant's standing eye level using a tape measure. Pilot testing determined that a throwing distance of 14 m encouraged a more forceful throw. Previous research indicates scaling up velocity is positively correlated to advances in overarm throwing technique (Southard, 2006). Participants were not blinded from knowledge of the results and verbal encouragement was provided; phrases included the words 'nice', 'well done' and 'good job'.

Data collection

Kinematic data were collected at 200Hz using an automated 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Three CX1 scanners provided a 360-degree field of view around the participant and were synchronized to two Kistler Force Platforms (9865, UK) flush to the floor. Active markers were placed on the estimated joint centre of rotation using a bilateral full body marker set. The anatomical points used were 3rd metacarpal, ulnar styloid process, forearm, lateral epicondyle of the elbow, shoulder, xiphoid process, greater trochanter, thigh, femoral condyle, lateral malleolus, calcaneus and 2nd metatarsal. Whole-body CoM was defined based on the mass and position of the individual segment CoM's of both hands, forearms, upper arms, shank, feet, and the head and torso were consider as a single segment (Plagenhoef, Evans & Abdelnour, 1983).

Following a residual analysis of the shoulder, elbow and wrist markers, a fourth-order Butterworth filter was applied to raw marker data with a cut-off frequency of 6 Hz (Winter, 2005). Data were analysed during the propulsive phase of the throw, defined from the start of forward and continuous motion of any marker in the direction of the throw until the frame of ball release. The data were analysed and presented as a percentage of the total propulsive phase of the throw and normalised to 100%.

Variables

Newell (1985) stages of coordination, control and skill: Coordination and variability of the CoM-wrist coupling in the anterior-posterior direction was quantified using a modified vector coding (VC) (Chang, Van Emmerik & Hamil, 2008; Needham, Naemi & Chockalingam, 2014; Sparrow, Donovan, Van Emmerik & Barry, 1987). VC angles were defined using four key coordination patterns: (1) anti-phase coupling ($112.5 \le \gamma < 157.5^\circ$, $292.5 \le \gamma < 337.5^\circ$) where variables are moving in opposite direction; (2) in-phase coupling ($22.5 \le \gamma < 67.5^\circ$, $202.5 \le \gamma < 247.5^\circ$) where variables are moving in the same direction; (3) wrist-led phase coupling ($0 \le \gamma < 22.5^\circ$, $157.5 \le \gamma < 202.5^\circ$, $337.5 \le \gamma < 360^\circ$) where wrist movement is dominant variable and; (4) CoM-led phase coupling ($67.5 \le \gamma < 112.5^\circ$ 2, $247.5 \le \gamma < 292.5^\circ$) where CoM movement is more dominant. Average of the standard deviation across the 101 point VC profiles of an individual was combined into the group analysis to determine beween group variability.

Components model (Roberton & Halverson, 1984): Action of the ‘step’ ‘trunk’, ‘humerus’ and ‘forearm’ were qualitatively classified by the principal investigator for all trials for all participants in line with the model description. A classification of 1 is representative of the least skilled action level, with action level 3 or 4 representative of skilled action of that component (Roberton & Halverson, 1984; Table 1). If a participant’s technique was split across two action levels for a component across the five throws the action level with the highest number of trials was recorded.

Bernstein (1967) joint range of motion: To capture the freeing of degrees of freedom, joint ROM during the propulsive phase of the throw was calculated. The ankle joint was defined from the 2nd metatarsal, lateral malleolus and calcaneus; knee joint from lateral malleolus, femoral condyle and greater trochanter; hip joint from femoral condyle, greater trochanter and xiphoid process; shoulder joint from shoulder joint centre of rotation, xiphoid process and lateral epicondyle of the elbow, elbow joint from shoulder joint centre of rotation, lateral epicondyle of the elbow, styloid process of ulna, and the wrist joint was defined from the 3rd metacarpal, styloid process of ulna and lateral epicondyle of the elbow. Average ROM across the 5 trials was calculated for each participant. The mean was calculated for each age group. Angles were defined in 3D where an angle of 180° would represent maximum extension, while 0° would represent minimal flexion.

Statistical analysis

Data were assessed for normality using a Shapiro-Wilks test. Once confirmed, a one-way analysis of variance (ANOVA) was conducted for each dependent variable ($p < 0.05$). Mauchly's test was used to determine the sphericity assumption within the data; where sphericity was violated, a Greenhouse-Geisser correction was applied. Comparisons of vector coding coordination variability were examined between age groups. Bonferroni post hoc correction was used as needed for multiple comparisons.

Results

3.1 Newell's (1985) stages of learning of coordination, control and skill

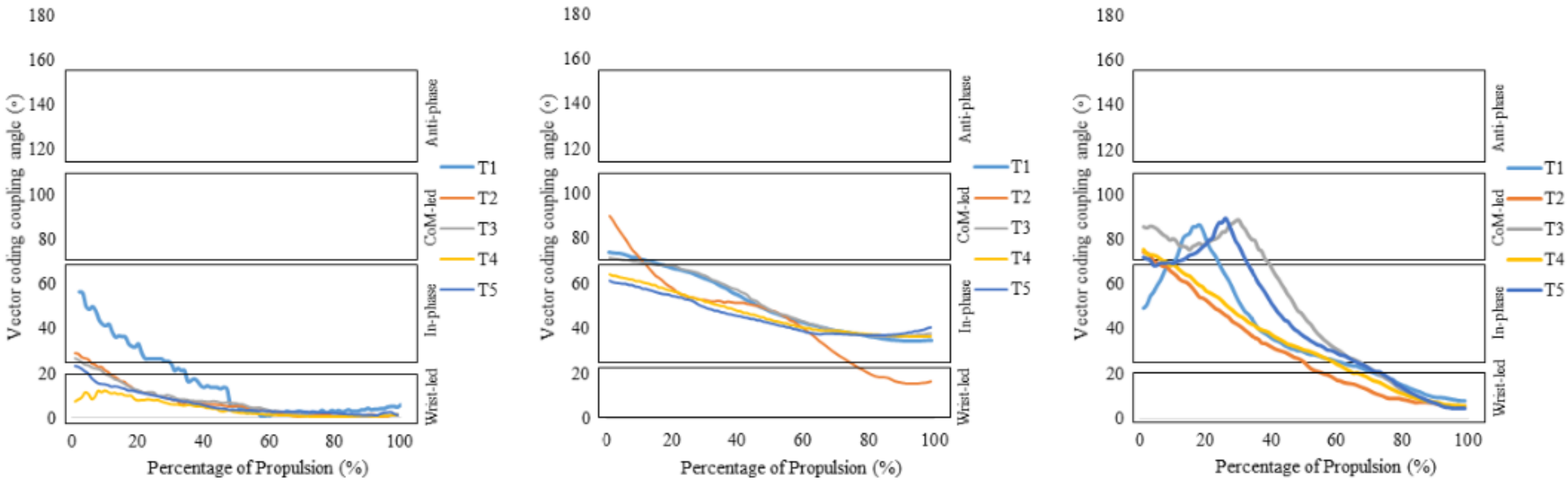

Fig 1. Vector coding angle between CoM-wrist coupling for 5 trials (Fig 1a, representative 6-year old; Fig 1b, representative 10-year old; and Fig 4.1c representative 14-year old).

Three CoM-wrist coupling modes were identified across the three age groups. Six-year olds tended towards in-phase coupling of the CoM-wrist at the start of the propulsive phase of the throw, where the CoM and wrist were moving forward together. Meanwhile for the majority of the propulsive phase, wrist-led coupling dominated at around 20% and continued towards ball release ($0 \leq \gamma < 22.5°$) (Fig 1a).

In line with Figure 1b all the 10 year olds and three of the six 14 year olds used CoM-led coupling at the start of the propulsive phase, progressing to in-phase coupling (at around 20%), finishing with wrist-led phase coupling at ball release (Fig 1b). The remaining three of the six 14 year olds exhibited CoM-led coupling at the start of the propulsive phase of the throw, which moved further into CoM-led coupling before progressing to wrist-led coupling at release (Fig 1c).

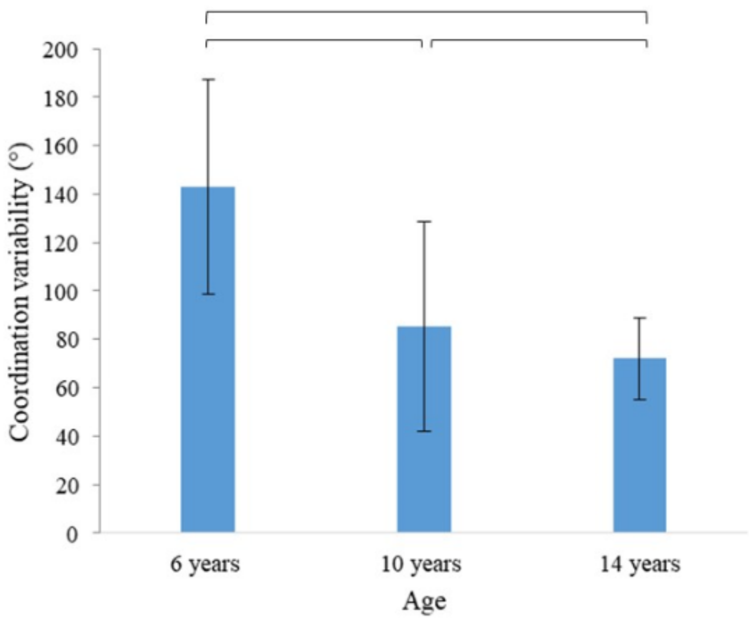

Fig 2. Standard deviation between subjects during 5 trials of the CoM-wrist coupling in the anterior posterior direction for dominant arm overarm throws at 6-, 10- and 14-years of age.

Significant differences were present in CoM-wrist coordination variability for dominant arm throws between 6, 10 and 14 years of age. Coordination variability of 6 year olds was significantly greater than 10 year olds ($p = 0.001$; $d = 0.67$) and 14 year olds ($p = 0.001$; $d = 1.72$). Coordination variability at 10 years of age was significantly greater than the 14 year old group ($p = 0.04$; $d = 0.14$).

3.2 Components model of overarm throwing (Roberton & Halverson, 1984)

Table 1. Action level at ages 6-, 10- and 14-years.

Segment	Action level	Description	6-yrs	10-yrs	14-yrs
Step	1	*No step.* Throws from initial foot position.	3		
	2	*Ipsilateral step.* The child steps with the foot on the same side as the throwing hand.	1		
	3	*Contralateral short step.* The child steps with the foot on the opposite side from the throwing hand.	2	6	6
	4	*Contralateral long step.* The child steps with the opposite foot a distance of over half the child's standing height.			
Trunk	1	*No trunk action.* No twist-up precedes the arm movement. If trunk action does occur, it accompanies the forward thrust of the arm by first extending and then flexing at the pelvis.	1		
	2	*Upper trunk rotation.* The spine and pelvis both rotate away from the intended line of flight and then simultaneously begin forward rotation.	5	6	6
	3	*Differentiated trunk rotation.* The thrower twists away from the intended line of ball flight and then, begins forward rotation with the pelvis while the upper spine is still twisting.			
Humerus	1	*Humerus oblique.* The humerus forms an oblique angle to the horizontal line of the shoulders during forward movement.	6		
	2	*Humerus aligned but independent.* The humerus forms a right a right angle to the trunk during forward movement, but at front facing has horizontally adducted to a positions ahead of the outline of the trunk.		6	6
	3	*Humerus lag.* At front facing, the humerus remains within the outline of the body.			
Forearm	1	*No forearm lag.* The forearm and ball move steadily forward to ball release.	6		
	2	*Forearm lag.* The forearm and ball appear to 'lag' i.e., to remain stationary behind the thrower of move downward or backward in relation to them.		6	6
	3	*Delayed forearm lag.* The lagging forearm delays reaching its final point of lag until the moment of front facing.			

Participants at 6, 10 and 14 years of age progressed through action levels of the components model (Table 1). The 6 years olds overarm throws were characterised by humerus and forearm action that was classified at action level 1. For the majority, trunk movement was characterised at action level 2, and step action distributed between level 1-3.

At 10 and 14 years overarm throws were characterised by more advanced action levels, but only the penultimate action level for each component. By 14 years, participants had not reached the highest action level of the components model for the 'step' component but had achieved this for the 'trunk', 'humerus' and 'forearm'.

3.3 Bernstein (1967) joint range of motion

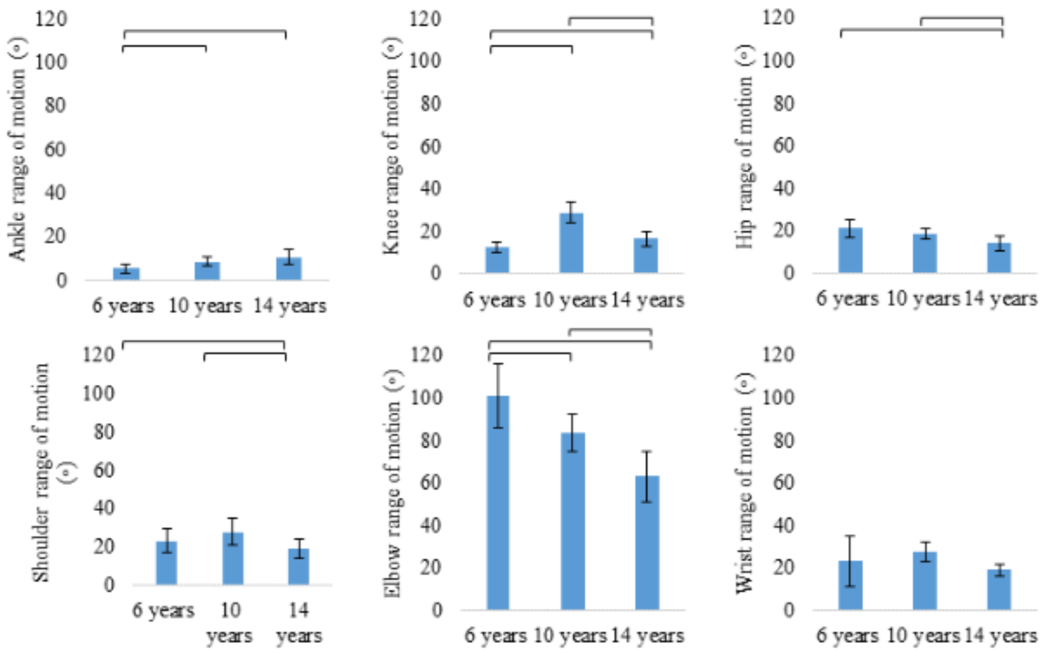

Fig 3. Joint range of motion at the ankle, knee, hip and shoulder, elbow and wrist during overarm throwing at 6-, 10- and 14-years of age.

Significant age differences were found in ROM in the majority of joints. Six year olds ankle ROM was significantly smaller than 10 year olds (ankle, $p = 0.003$) and 14 year olds ($p = 0.001$). Knee ROM at 6 years was significantly smaller than at 10 years ($p = 0.002$) and 14 years ($p = 0.01$), however, greater at 10 years compared to 14 years ($p = 0.003$). Hip ROM was significantly greater in 6 year old age group compared to 10 year olds ($p = 0.01$) and 14 year olds ($p = 0.007$). Shoulder ROM at 14 years was signficantly smaller than at 6 years ($p = 0.02$) and 10 years ($p = 0.03$). Elbow ROM was significantly greater at 6 years compared to 10 years (elbow, $p = 0.001$) and 14 years ($p = 0.001$). The 6 year olds wrist ROM was significantly smaller compared to 10 year olds ($p = 0.04$) and greater than 14 year olds ($p = 0.03$), whereas 10 year olds were significantly greater compared to 14 year olds ($p = 0.02$).

Discussion

The aim of this paper was to investigate the differences in technique over childhood and adolescence during dominant overarm throwing with respect to three different, though potentially complementary, approaches to qualitative and quantitative change of movement dynamics: Newell's (1985) stages of learning coordination, control and skill; the component model of overarm throwing (Roberton & Halverson, 1984); and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom. The key findings included more advanced CoM-wrist coupling profile where the coupling progressed through a greater range of phase relations with increments of age, the use of a contralateral step and increased ROM at the ankle and knee joint with age.

Newell's (1985) stages of learning coordination, control and skill

It was anticipated that the older children in this study would display more developed overarm throwing action (Langendorfer & Roberton, 2002; Stodden et al., 2006). In order to gain a macroscopic overview of changes in technique and apply Newell's (1985) stages of learning model the CoM-wrist coupling was studied. The macroscopic organisation of the system became more complex with age (Fig 1b; Fig 1c), providing evidence in line with that shown by Palmer et al. (2018) for adults learning to throw with the non-dominant arm. This was demonstrated by children at 10 and 14 years of age utilising a broader range of phase relations associated with the arm kinematics chain. While this macroscopic variable does not describe the nuances of technique, it was able to capture a transition in system organisation despite individual differences that influenced joint-space organisation.

Palmer et al. (2018) showed that CoM-wrist coupling captured robust characteristics of technique change across adult participants during non-dominant arm practice. The current study showed more advanced modes of CoM-wrist coupling patterns emerged with age which could be generalizable to the motor learning of all advanced skills. Specifically, coupling mode 1 and 2 (Fig 1a; 1b) displayed a similar but simpler profile than previously reported by Palmer et al. (2018) as the children spent less time in-phase coupling (mode 1; Fig 1a) and CoM-wrist led coupling (mode 2; Fig 1b). Coupling mode 3 (Fig 1c) was similar to the coupling reported by Palmer et al. (2018), while the progression of coupling angle further into the CoM-led coupling was a progression not present for adult participants. These differences in findings could be due to differences in dynamical degrees of freedom and potentially different postural control of the CoM in children compared to adults learning to throw.

The current findings provide support for global macroscopic variables being associated with common inter-individual changes during learning which are not seen at the joint-space level of technique changes. Intra-individual coupling variability decreased with the progression of age from 6 to 14 years (Fig 2), suggesting that older children were able to produce more consistent CoM-wrist coupling patterns than younger children (Fig 2). Based on the reduction of variability for the older children it is suggested that they may have reached the control stage of learning (Newell, 1985). Meanwhile younger children displayed higher variability suggesting they remained in the initial coordination stage (Newell, 1985); although it should be acknowledged that this is only relative. This pattern of findings is consistent with Wagner et al. (2012) who reported that movement variability decreased with skill level in the standing throw and was associated with skilled players having the ability to compensate for any increases in movement variability. To provide further evidence for reduction in variability and changes from coordination to control stages, further research is still needed, with different skills and longer periods/more distinct groups being observed.

The application of a postural (CoM) and end-effector (wrist) macroscopic variable approach raises an important distinction regarding the level of the dynamical system that might capture fundamental characteristics of technique change. This stands as an epistemological shift from the joint-space level of analysis in previous research (Bernstein, 1967; Chow et al., 2008; Newell et al., 1989; Vereijken et al., 1992).

To understand the kinematics associated with the macroscopic dynamics, technique changes were examined using the components model (Roberton & Halverson, 1984) and Bernstein's (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom.

The components model of overarm throwing (Roberton & Halverson, 1984)

Six year olds were the least skilled at overarm throwing as categorised by the components model (Roberton & Halverson, 1984; Table 1). They also displayed the greatest range of step action configurations of the three age groups (Table 1), including no step and ipsilateral step configurations. These step configurations create a closed body position and place constraints on the body that limit progression in 'humerus' and 'forearm' components through restricting rotation of the trunk and preventing the production of angular velocity (Stodden et al., 2006*a*). Ten and fourteen year olds all displayed a contralateral, short step (Table 1), however, no further qualitative technique changes were found between 10 and 14 years of age suggesting technique were similar.

No participants displayed the most advanced step or trunk action, suggesting that overarm throwing action is not necessarily fully developed by 14 years of age. While the trunk and arm segments are highlighted as invaluable contributors to overarm throwing action (Nelson et al., 1991; Roberton & Konczak, 2001), it might be that movements related to the step are currently more critical to the development of technique than other key biomechanical parameters such as segmental lag and the kinematic chain between torso and arm segments. Halverson et al. (1982) reported that by 13 years of age their participants were far from having 'mastered' or 'developed proficiency' in overarm throwing. While Stodden et al. (2006*a,b*), examined cross-sectional kinematic variables in dominant arm throwing in children between 3 to 15 years of age, it was reported that a developmental level at 6 years of age to be in line with current findings. However, children between 11 to 13 years displayed more advanced developmental action levels (level 3 and level 4).

Bernstein (1967) joint range of motion

Consistent with Bernstein's hypothesis (1967) ROM of the ankle and knee joint increased with age (Fig 3) and occurred along with a more advanced 'step' action (Table 1). Interestingly ROM of the hip and elbow decreased with age from 6 to 14 years of age (Fig 3). In parallel, children at 10 and 14 years of age were categorised in advanced action levels of the 'humerus' and 'forearm' of the components model

(Roberton & Halverson, 1984).

The findings lead to the suggestion that the ankle, hip and elbow specifically, might distinguish age-related differences between child throwers, and might be a key coaching point for the skill. However, the context to these increased ROM's is likely captured within the Roberton and Halverson (1984) components model which outlines key coaching points.

Integrating frameworks to the acquisition of overarm throwing

Emphasising a CoM-wrist coupling as a macroscopic variable over control of individual degrees of freedom is based on the theoretical proposition that motor learning is associated with change in the overall system dynamics (Kelso, 1995; Newell & Vaillancourt, 2001). Arguably, the use of CoM-wrist coupling as the macroscopic variable, is underpinned by the technique changes seen in the components model (Roberton & Halverson, 1984).

In supporting these different emphases on system organisation, the findings imply that a more advanced CoM-wrist coupling is achieved during skill progression throughout childhood by taking a contralateral step during throwing, which is associated with increased ROM of the lower extremities. By increasing the complexity of the macroscopic dynamics, participants followed the sequence of components change in the Roberton and Halverson (1984) model, while Bernstein's (1967) postulation of freeing the mechanical degrees of freedom was limb specific.

The findings of this paper support the theoretical proposition that motor control is organized with respect to overall system dynamics rather than the control of individual degrees of freedom (Kelso, 1995; Newell, 1985). The macroscopic variable linking torso motion to ball release was more able to distinguish differences in overarm throwing technique among the three age groups than single joint motions, and therefore, might be key to understanding the dynamics of technique change from a dynamical systems theory perspective. Moreover, the findings highlight the importance of the lower extremities and dynamic postural control in overarm throwing in what is usually characterised as an upper extremity action.

Finally, the cross-sectional design of the current study means that the age manipulation is also in some ways and to some degree a general experience or more specific practice effect. A long history of motor development research has provided support for the interaction of nature and nurture effects in the emergence of the fundamental skills (Haywood & Getchell, 2019), including throwing (Roberton et al., 1982; Wickstrom, 1977). The study reported here was not designed to investigate the nature–nurture interaction in the development of throwing but it can be usefully contrasted to the findings of Palmer et al. (2018) where adults with the non-dominant arm enhanced their CoM to wrist coupling as a function of throwing practice. This provides support for the inference here of the influence of practice on the different qualitative and quantitative variables that capture learning to throw overarm from early through later childhood.

A limitation of this study includes the lack of an outcome measure in terms of target accuracy and ball speed. Therefore, in order to understand other sources of constraints of coordination dynamics during overarm throwing, future work looks to explore the effects of age and skill level on throwing technique with a larger sample group. In addition, the target distance of 14 m provides a specific task constraint which may have affected the results of the study. In line with this, it is of interest to manipulate throwing distance and target size in future work, in order to explore the mediating effects of a speed-accuracy trade-off across age and skill level groups.

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